

# THE LUMINOUS AND CARBON-RICH SUPERNOVA 2006GZ: A DOUBLE DEGENERATE MERGER?

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## ABSTRACT

Spectra and light curves of SN 2006gz show the strongest signature of unburned carbon and one of the slowest fading light curves ever seen in a type Ia event ( $\Delta m_{15}(B) = 0.69 \pm 0.04$ ). The early-time Si II velocity is low, implying it was slowed by an envelope of unburned material. Our best estimate of the luminosity implies  $M_V = -19.74$  and the production of  $\sim 1.2M_\odot$  of  $^{56}\text{Ni}$ . This suggests a super-Chandrasekhar mass progenitor. A double degenerate merger is consistent with these observations.

*Subject headings:* supernovae: general — supernovae: individual(SN 2006gz)

## 1. INTRODUCTION

The conventional picture for Type Ia supernovae (SN Ia) is that they are thermonuclear explosions of C-O white dwarf stars (WD). Two possible routes to explosion have been explored: single degenerate (SD) models in which the WD is nudged to explosion by accretion from a binary companion, and double degenerate (DD) models in which two WDs merge.

SN Ia have been the essential tool in establishing the Hubble constant (e.g., Jha et al. 1999; Riess et al. 2005), showing a sub-critical matter density (Garnavich et al. 1998; Perlmutter et al. 1998), and demonstrating that the cosmic expansion is accelerating (e.g., Riess et al. 1998; Perlmutter et al. 1999). Yet the precise nature of SN Ia progenitors remains uncertain.

In the SD scenario, there is only a narrow range of physical conditions for accretion to increase the WD mass over time. (see Yoon & Langer 2003, and references therein). The DD pathway may lead to neutron star formation (Saio & Nomoto 2004), but recent studies suggest explosion as a SN Ia is possible (Yoon, Podsiadlowski, & Rosswog 2007). Both scenarios may contribute to the SN Ia population so it is important to consider their observable differences.

The presence or absence of carbon and its velocity distribution should be strong clues to the nature of the explosion. For example, multi-dimensional calculations of pure deflagrations predict that unburned material should be mixed into low-velocity layers (e.g., Gamezo et al. 2003). The fact that carbon is not commonly seen in deep layers suggests that most SN Ia are not a result of pure deflagration.

Carbon is most often weak or absent in optical and infrared spectra of SN Ia (Branch et al. 2003; Marion et al. 2006; Thomas et al. 2006). This suggests that burning to intermediate mass elements takes place in the outer layers of a C-O WD for most SN Ia. The model that matches this feature best is a delayed detonation in a SD system since DD merger and pulsating delayed det-

onation (PDD) explosions are likely to leave significant unburned material in the outer layers (Khokhlov et al. 1993). Conversely, the presence of carbon raises the possibility of a DD merger. DD mergers could also have masses and luminosities that extend beyond the Chandrasekhar limit. Two recent SN Ia may have been merger events: the extremely luminous SN 2003fg was interpreted by Howell et al. (2006) as arising from a super-Chandrasekhar (S-Ch) progenitor, and a compressed silicon layer in SN 2005hj provides indirect evidence for an unburned layer atop the silicon (Quimby et al. 2007).

Here we present spectra and light curves<sup>5</sup> of the type Ia supernova 2006gz that begin two weeks before maximum light. They directly show the strongest signature of unburned carbon ever reported and a low silicon velocity at very early times. The light curve is very broad and luminous, approaching the luminosity of SN 2003fg. These properties suggest that SN 2006gz may have arisen from the merger of two WDs.

## 2. OBSERVATIONS

SN 2006gz was discovered by Puckett & Pelloni (2006) and independently by Winslow & Li (2006) on 2007 Sept. 26.0 (UT). It was classified as a type Ia event by Prieto et al. (2006a) who noted an unusual double absorption feature instead of the typical Si II 6355Å line. The supernova was 12" west and 28" south of the center of the Scd spiral galaxy IC 1277, corresponding to a projected distance of 14.4 kpc. It should be noted that the 21-cm H I radio-based redshift of 0.0280 (Haynes et al. 1997) is incorrect. We report  $z=0.0237 \pm 0.0004$  based on our optical spectrum of IC 1277, in close agreement with other optical redshifts reported in NED<sup>6</sup>.

Seven spectra were obtained with the 2.4-m MDM telescope and The Ohio State University Boller and Chivens CCD spectrograph beginning 2006 Sept. 28.1 (UT), 14 days before maximum light. A 2" slit and a 150 line/mm grating were used. The resolution was  $\sim 15\text{\AA}$ .

A series of 10 spectra was taken with the Fred L. Whipple Observatory (FLWO) 1.5-m Tillinghast telescope and FAST spectrograph (Fabricant et al. 1998), also starting Sept. 28.1 (UT). A 3" slit and 300 line/mm grating were mounted. The resolution was  $\sim 7\text{\AA}$ .

Beginning Sept. 29.1 (UT), 23 nights of  $UBVR'i'$  pho-

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<sup>5</sup> Available at <http://www.cfa.harvard.edu/supernova/SN2006gz>

<sup>6</sup> <http://nedwww.ipac.caltech.edu/>

tometry were acquired on the FLWO 1.2m telescope and Keplercam instrument. Eleven comparison stars were calibrated on 4 photometric nights in *BV*, 3 nights in *r'i'*, and 1 night in *U*, with a typical *V*-band uncertainty of 0.014 mag per star. Host galaxy subtraction images were taken in *BVr'i'* on 2007 May 27.4 (UT) and in *U* on June 27.4 (UT), after SN 2006gz had faded sufficiently.

### 3. ANALYSIS

#### 3.1. Spectra

The FLWO and MDM spectra taken at  $-14$  days both show features typical of a type Ia supernova. As seen in Figure 1, intermediate-mass elements (Si II, S II and Ca II) are clearly present. Prieto et al. (2006a) noted that the most unusual aspect of the early spectra is the extra absorption seen redward of the Si II 6355Å feature. Absorption features at this wavelength have been identified with C II 6580Å (Branch et al. 2003; Thomas et al. 2006). Using the SYNOW code to generate synthetic spectra (Fisher et al. 1999), C II and Na I reproduce this feature and the absorption at 5490Å better than a combination of H I and He I. We adopt this interpretation. C II lines at 4745Å and 7234Å may also be seen before  $-10$  days. At two weeks before maximum light the C II feature has a rest-frame equivalent width (EW) of 25Å in SN 2006gz, while in SN 1990N (Leibundgut et al. 1991; Jeffery et al. 1992) the feature is seen at 5Å EW. Thomas et al. (2006) reports a strong C II detection in SN 2006D with 7Å EW at  $-7$  days. In the case of SN 2006gz, the C II absorption strength is comparable to the Si II EW of 37Å at  $-14$  days but quickly weakens and is undetectable past  $-10$  days (Figure 2). The Si II EW increases after the initial spectrum and reaches 70Å near maximum brightness.

Unlike the luminous and slowly declining SN 1991T, the spectra before maximum light are not dominated by Fe III lines. But the ratio of Si II 5972 to the 6355Å line seen here does correspond to the values seen in other very slowly declining SN Ia (e.g., Garnavich et al. 2004). Except for the 5972Å feature, many of the Si II lines in SN 2006gz are particularly deep and narrow, including 3858Å and 4130Å. There is also a strong Si III line (4560Å) and Si III may also be the source of the absorption observed at 5500Å (Branch et al. 2003).

We measure the Si II velocity to be  $\sim 13100$  km s $^{-1}$  at  $-14$  and  $-13$  days, in contrast to  $\sim 15500$  km s $^{-1}$  in SN 1990N at  $-14$  days (Figure 2). But the SN 2006gz C II velocity is similar to the silicon velocity in SN 1990N and SN 1994D before  $-11$  days (Patat et al. 1996). The Si II velocity does not show the rapid decline that was observed in other SN Ia before  $-7$  days. At  $-10$  days it is at  $\sim 12500$  km s $^{-1}$  and declines by only 1000 km s $^{-1}$  to 11500 km s $^{-1}$  by maximum light. In four cases of SN Ia caught in early phases (1990N, 1994D, 2002bo, and 2003du) the Si II velocities at  $t < -10$  days were 2000 to 4000 km s $^{-1}$  higher than that at maximum light (Benetti et al. 2005). In SN 2006gz, the velocity of the Si II is unusually low and constant at the earliest times, possibly as a result of overlying material for which the C II line is evidence. A tantalizing hint of an early plateau in velocity is suggested by the unchanging velocities in both Si II and C II between days  $-14$  and  $-13$ . After  $-7$  days, the Si II velocity slowly declines, with a slope similar to

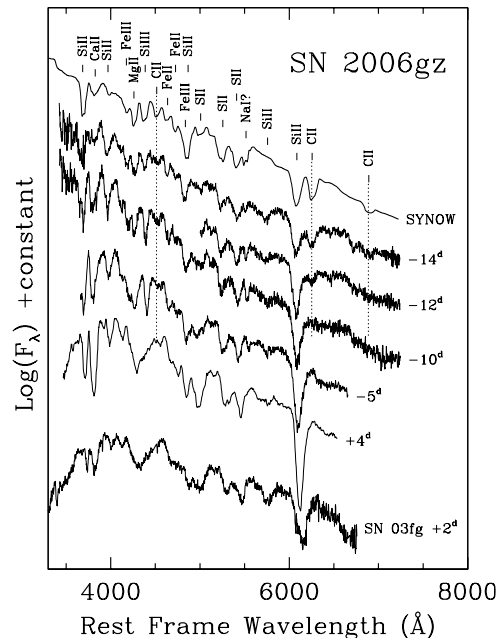


FIG. 1.— SN 2006gz spectra at 5 epochs. SN 2003fg at  $+2$  days and a SYNOW fit to the MDM spectrum at  $-14$  days are shown. Dotted lines: C II  $\lambda\lambda 4745$ , 6580, and 7234 blueshifted by 15500 km s $^{-1}$ .

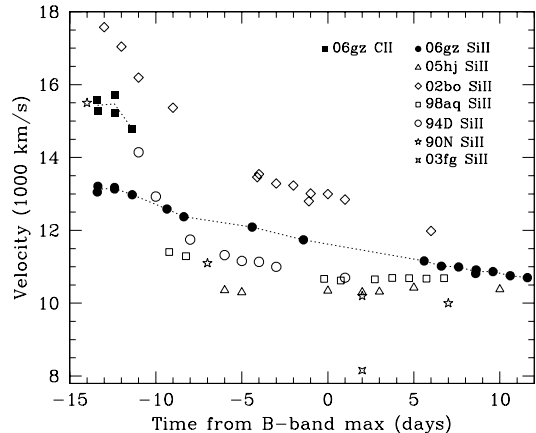


FIG. 2.— Si II and C II velocities. Up until  $-12$  days, Si II is suppressed in SN 2006gz while its C II velocity is comparable to that of Si II in SN 1994D and 1990N. SN 2006gz velocities are consistent within the error bars (not shown) for nights with measurements from both telescopes.

SN 1990N and SN 1994D.

In the DD merger models (and PDD models) studied by Khokhlov et al. (1993), the detonation of the dense C-O occurs within a low-density C-O envelope. The unburned envelope compresses the outer, partially burned material, creating a density enhancement in the silicon layer which slows the photosphere from receding into lower-velocity layers. In SN 2005hj, Quimby et al. (2007) inferred the presence of overlying material from the ob-

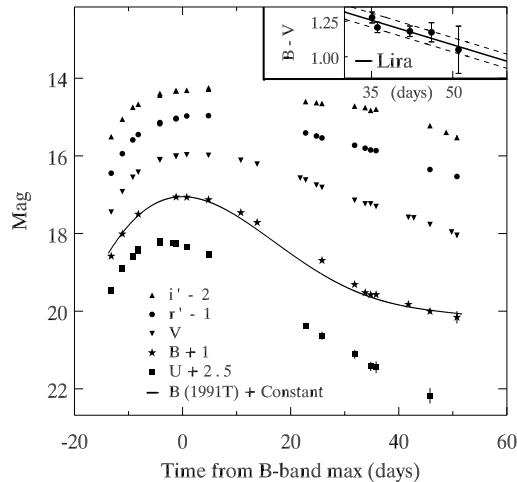


FIG. 3.— SN 2006gz  $UBVr'i'$  light curves.  $B$ -band has a faster rise and slower decline than SN 1991T. Inset:  $B - V$  from +35 to +51 days, with  $E(B - V)_{Gal} = 0.063$  removed. The Lira relation, offset by  $E(B - V)_{host} = 0.18 \pm 0.05$ , is shown.

served velocity plateau, but they did not have direct evidence for a carbon-rich layer. In SN 2006gz, carbon is definitely present, but the possible velocity plateau is very brief and very early.

### 3.2. Light Curve, Reddening and Luminosity

SN 2006gz has one of the broadest light curves (Figure 3) of any SN Ia ever measured: its 15-day  $B$ -band decline from maximum light is  $\Delta m_{15}(B) = 0.69 \pm 0.04$ , with  $t_{max}(B) = 2454020.2 \pm 0.5$  JD. The rise time of  $16.6 \pm 0.6$  days is very short for the slow decline and does not fit the positive correlation between rise and decline time in light curve fitters such as MLCS2k2 (Jha, Riess, & Kirshner 2007) and dm15 (Prieto et al. 2006b). Strovink (2007) find evidence for a bimodal SN Ia rise time distribution based on a sample of 8 objects:  $16.64 \pm 0.21$  days and  $18.81 \pm 0.36$  days. The decline rate is also outside the range used to construct these fitters. The  $i'$ -band peaks several days after  $B$  and does not appear to have the pronounced trough or second peak expected for a very luminous SN Ia. For comparison, SN 2001ay has  $\Delta m_{15}(B) \sim 0.6 - 0.7$  but its luminosity of  $M_V \sim -19.2$  is significantly lower than expected for its decline rate (Phillips et al. 2002). Slow-declining and overluminous SN Ia are found almost exclusively in late-type galaxies while fast-declining and subluminous SN Ia are usually found in early-type hosts (e.g., Jha, Riess, & Kirshner 2007). Mannucci, Della Valle, & Panagia (2006) show that there may be 2 populations of SN Ia progenitors: a promptly-exploding component that dominates the supernova rate in star-forming galaxies, and a "tardy" one that gives rise to most of the SN Ia in older hosts. How the SD and DD pathways may relate to the correlation between luminosity and host type, and to the prompt and tardy progenitor components, needs further investigation.

The luminosity and extinction of SN 2006gz in  $UBV$  are given in Table 1. We correct for Galactic reddening using the dust maps of Schlegel, Finkbeiner, & Davis (1998) and apply  $K$ -corrections. We use a Hubble-flow distance modulus of  $\mu = 34.95 \pm 0.04$  ( $z_{cmb} = 0.0234$ ,  $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0.7$ , and a pe-

culiar velocity uncertainty of  $300 \text{ km s}^{-1}$ ) to get absolute luminosities of  $M_B = -19.17 \pm 0.04$ , and  $M_V = -19.19 \pm 0.04$ , before correction for host reddening.

There are, however, 2 pieces of evidence for host reddening. First, the Na I absorption at the SN position has an  $EW = 0.30 \pm 0.15 \text{ \AA}$ , giving rise to  $E(B - V)_{host} \leq 0.15 \pm 0.08$  (Turatto, Benetti, & Cappellaro 2002). Second, the  $B - V$  color shows normal, albeit slow, evolution. It increases by  $\sim 1.3$  mag between maximum light and 35 days after. We apply  $K$ -corrections and correct for time dilation and Galactic reddening in the  $B - V$  color curve. From +35 to +51 days, SN 2006gz has a color evolution consistent with the Lira relation (Lira 1995), implying a host color excess of  $E(B - V)_{host} = 0.18 \pm 0.05$  (Figure 3). We adopt this while cautioning that it may be incorrect if Lira's relation does not apply. Since the spectra are normal after  $-10$  days, and the Lira-corrected  $B - V$  and  $U - B$  colors at maximum are consistent with those reported in Figure 9 of Jha et al. (2006), it is not unreasonable to assume that Lira's relation applies.

The correct value of the reddening law for SN Ia is under active study (Conley et al. 2007). We use  $R_V = 3.1$  and  $R_V = 2.1$  to give a wide range of plausible host extinctions and we calculate absolute magnitudes for SN 2006gz (see Table 1). Using  $R_V = 3.1$  gives  $M_B = -19.91 \pm 0.21$ , and  $M_V = -19.74 \pm 0.16$ , with  $B - V = -0.17 \pm 0.05$ . This is comparable to the possibly S-Ch SN 2003fg, which had an absolute magnitude of  $M_V = -19.85 \pm 0.06$  ( $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ) and a color of  $B - V \sim -0.15$ , implying its host reddening was quite small. The case of  $R_V = 2.1$  gives  $M_V = -19.56 \pm 0.11$  for SN 2006gz.

We also calculated a UVOIR light curve of SN 2006gz with  $L_{bol}(t_{max}) = (2.18 \pm 0.39) 10^{43} \text{ erg s}^{-1}$  for  $R_V = 3.1$ . We follow the procedure of Stritzinger et al. (2006) to derive a  $^{56}\text{Ni}$  mass ( $M_{Ni}$ ) of  $1.20 \pm 0.28 M_\odot$ . For  $R_V = 2.1$ ,  $M_{Ni} = 1.02 \pm 0.21 M_\odot$ . The detonation of a  $1.4 M_\odot$  WD can produce  $\sim 0.9 - 1.0 M_\odot$  of  $^{56}\text{Ni}$  (Khokhlov, A. 2007, private communication). In figure 4, we plot  $M_{Ni}$  against  $\Delta m_{15}(B)$  for the 16 SN Ia in Stritzinger et al. (2006) and add SN 2006gz, SN 2003fg, and SN 2001ay (Phillips et al. 2006).

The DD merger models of Khokhlov et al. (1993) consist of a  $1.2 M_\odot$  WD detonation inside C-O envelopes of different masses. They produce  $0.63 M_\odot$  of  $^{56}\text{Ni}$ . The envelope decelerates the layers of the exploded WD, increases their density, and thus raises the diffusion time. This produces broader light curves, as seen in SN 2006gz after maximum. Merger models with larger, S-Ch primary WDs should be explored to see if they can explain the properties of SN 2006gz. A different cause of the fast rise time and high luminosity could be an off-centered explosion, with the nickel-rich region towards us (Hillebrandt, Sim, & Röpke 2007).

## 4. DISCUSSION AND CONCLUSION

The three outstanding features of SN 2006gz are the presence of carbon, the low early-time silicon velocity, and the luminous, broad light curve.

SN 2006gz shows the strongest evidence for unburned carbon of any SN Ia observed to date. The strong carbon feature has a higher expansion velocity than the silicon and fades quickly. The carbon is part of the photosphere at early times. The obvious inference is that the explo-

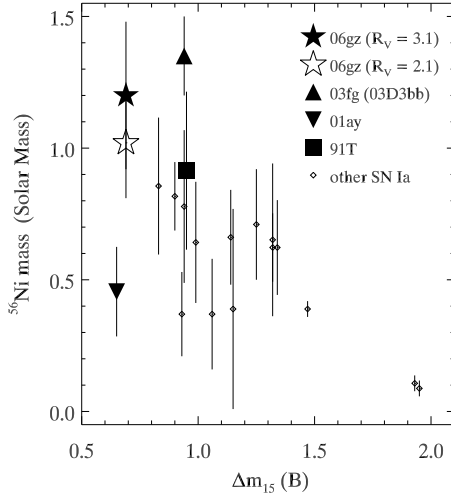


FIG. 4.—  $^{56}\text{Ni}$  mass v.  $\Delta m_{15}(B)$  for both reddening cases of SN 2006gz. Also shown are 16 SN Ia from Stritzinger et al. (2006), and SN 2003fg (Howell et al. 2006), and SN 2001ay (Phillips et al. 2006). SN 2006gz and SN 2003fg may come from S-Ch progenitors.

sion did not burn all the carbon. This could be explained by the outer WD C-O layer being accelerated and diluted during a deflagration phase. It is also possible that the envelope of the DD merger could be shocked and accelerated within the first few seconds of explosion and give rise to the observed carbon.

The unusually low and slowly declining silicon velocity at early times, combined with the deep and narrow silicon absorption features, have been predicted by DD merger models.

The light curve is one of the broadest SN Ia ever seen with  $\Delta m_{15}(B) = 0.69 \pm 0.04$ . If it obeys the Lira relation

then it produced  $M_{\text{Ni}} = 1.20 \pm 0.28 M_{\odot}$  ( $R_V = 3.1$ ) or  $M_{\text{Ni}} = 1.02 \pm 0.21 M_{\odot}$  ( $R_V = 2.1$ ). Combined with this, the presence of copious silicon and other non-iron-peak elements rules out a SD detonation and makes a S-Ch progenitor a good possibility. In both SD and DD cases, the centrifugal force of rotation can allow WDs to grow beyond  $1.4 M_{\odot}$ . However, the DD scenario is simpler in the sense that no helium or hydrogen shell burning is required to build up the primary WD.

Taken separately, the three main features of SN 2006gz can be explained by various models. First, the unburned carbon is plausible to different degrees in the SD and DD scenarios. Second, the suppressed silicon velocity is predicted by DD models. Third, the luminous and broad light curve with high implied  $^{56}\text{Ni}$  mass is possible in SD and DD models. However, taking all of these features together points to a consistent picture in which SN 2006gz is the result of the merger of two white dwarfs.

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TABLE 1  
EXTINCTION AND ABSOLUTE MAGNITUDE AT MAXIMUM LIGHT WITH  $E(B - V)_{host} = 0.18(05)$

| X-band | $m_X$ | $A_X(Gal)$ | $K\text{-cor}$ | $A_X(host)=0$ | $R_V = 2.1$ |            | $R_V = 3.1$ |            |
|--------|-------|------------|----------------|---------------|-------------|------------|-------------|------------|
|        |       |            |                | $M_X$         | $A_X(host)$ | $M_X$      | $A_X(host)$ | $M_X$      |
| U      | 15.77 | 0.34       | 0.17           | -19.70        | 0.67(19)    | -20.37(19) | 0.87(24)    | -20.57(25) |
| B      | 16.06 | 0.27       | 0.01           | -19.17        | 0.56(16)    | -19.73(16) | 0.74(21)    | -19.91(21) |
| V      | 15.99 | 0.21       | 0.02           | -19.19        | 0.38(11)    | -19.56(11) | 0.56(16)    | -19.74(16) |